Trends in Concentrator Photovoltaics

ARPA-E Workshop on High-Efficiency, High-Concentration Photovoltaics Through Advanced Optical System Design

March 28, 2012

Daniel J. Friedman

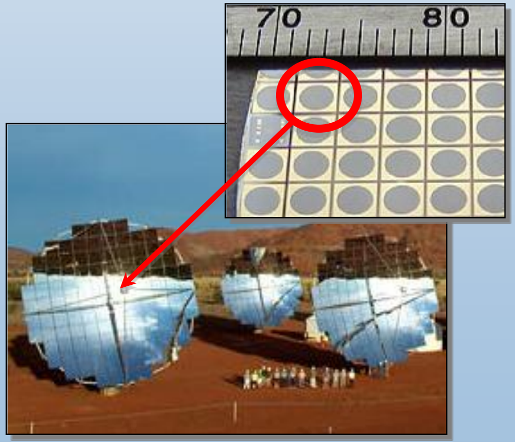
National Renewable Energy Laboratory

Fundamental Constraints

CPV and the Two Challenges of PV

Sunlight is
•Not power-dense – only ~1kW/m^2
•Broad spectrum

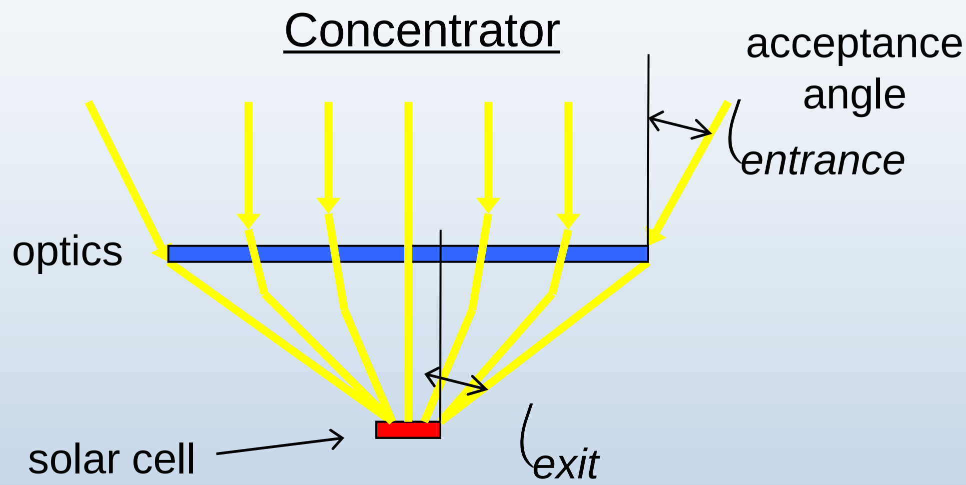
Multijunction CPV addresses both challenges
•Light-gathering (fresnel lenses, mirrors) boosts effective power density to more useful levels
•Multijunctions efficiently extract power from sunlight's broad spectrum
•What's next?



Fundamental Limits to Concentrator Optics

Maximum possible point-focus concentration is

$$C_{2D} \le \left(\frac{n\sin(\theta_{exit})}{\sin(\theta_{entrance})}\right)^2$$



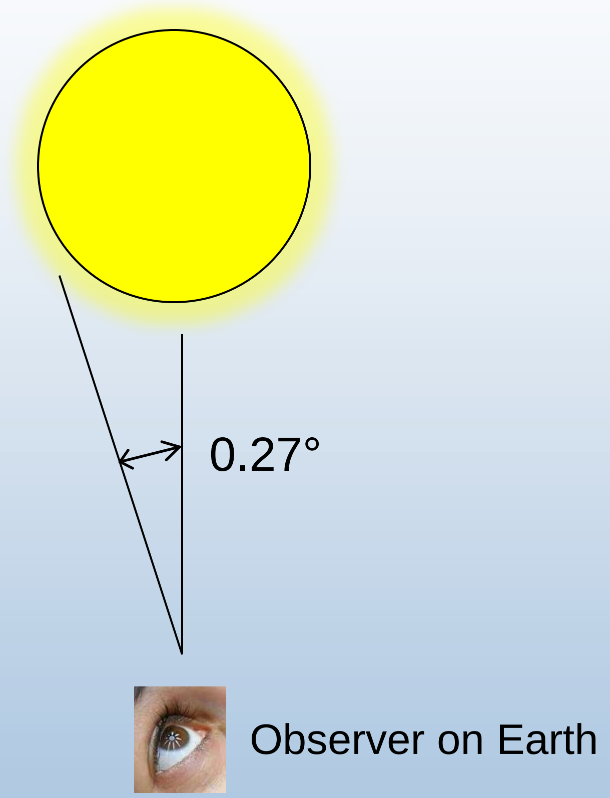
Want high concentration, large $\theta_{entrance}$, non-grazing θ_{exit}

Can't have them all – *must trade off*

Focusing the Sun

Sun’s disk cannot be concentrated by more than ~46000 n^2

Want tracking tolerance of 1°?
Then max conc. ~2000 n^2



Optics and Tracking

Concentrators have to be pointed at the sun, or "tracked", throughout the day

Required pointing accuracy increases with concentration

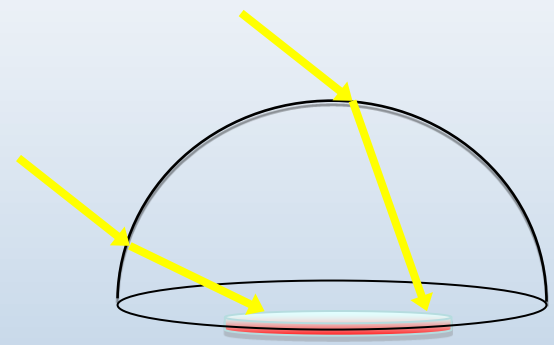
increases expense, challenges reliability

Clever optical design can increase angular acceptance, mitigating tracking requirements

Concentrating the Entire Sky?

If we could concentrate light from the entire sky:

- Would collect non-direct light
- Wouldn't have to track



$\theta_{entrance} = 90°$, so

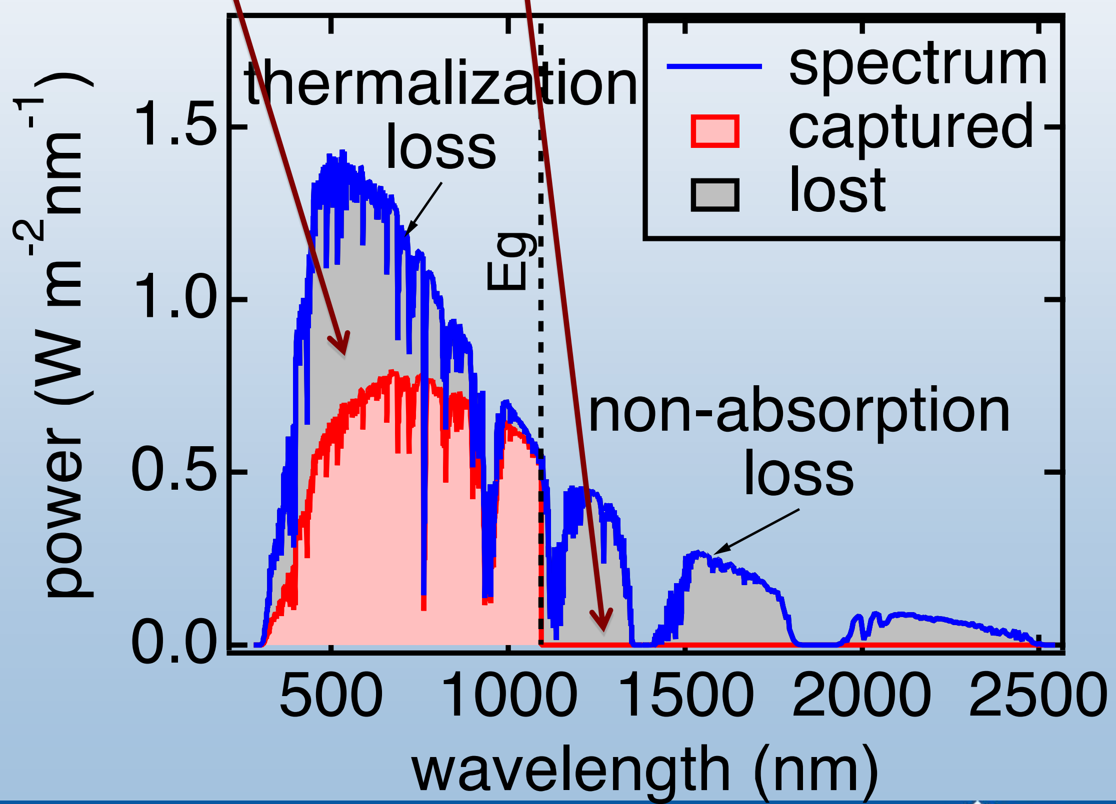
Max conc. = n^2

With n=1.5, get a concentration of ~2

Technically possible, but not cost-effective

Fundamental Limits to Single-Junction Efficiency

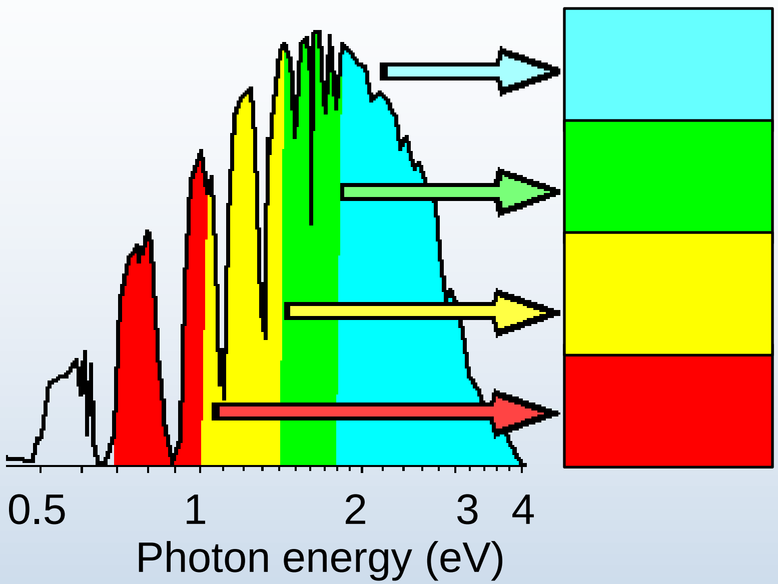
Shockley-Queisser postulate:
Photon at energy $h\nu$ into bandgap E_g delivers energy:
Eg for ($h\nu > E_g$); **0** for ($h\nu < E_g$)



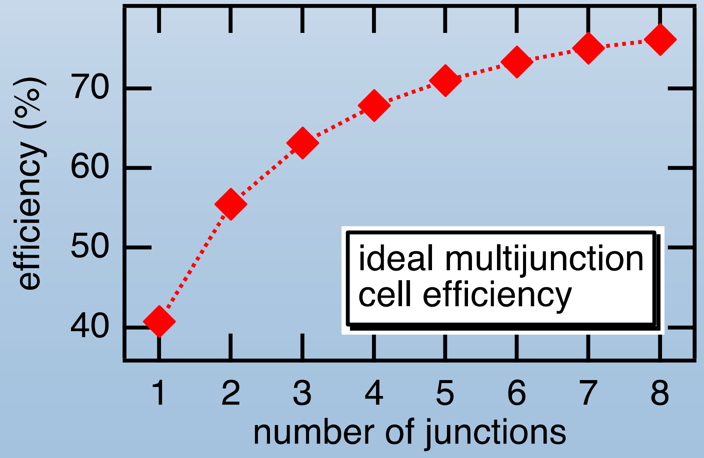
Overcoming the Single-Junction Limit

Reduce thermalization losses

Capture broader region of the spectrum



Allows us to beat the single-junction efficiency limit

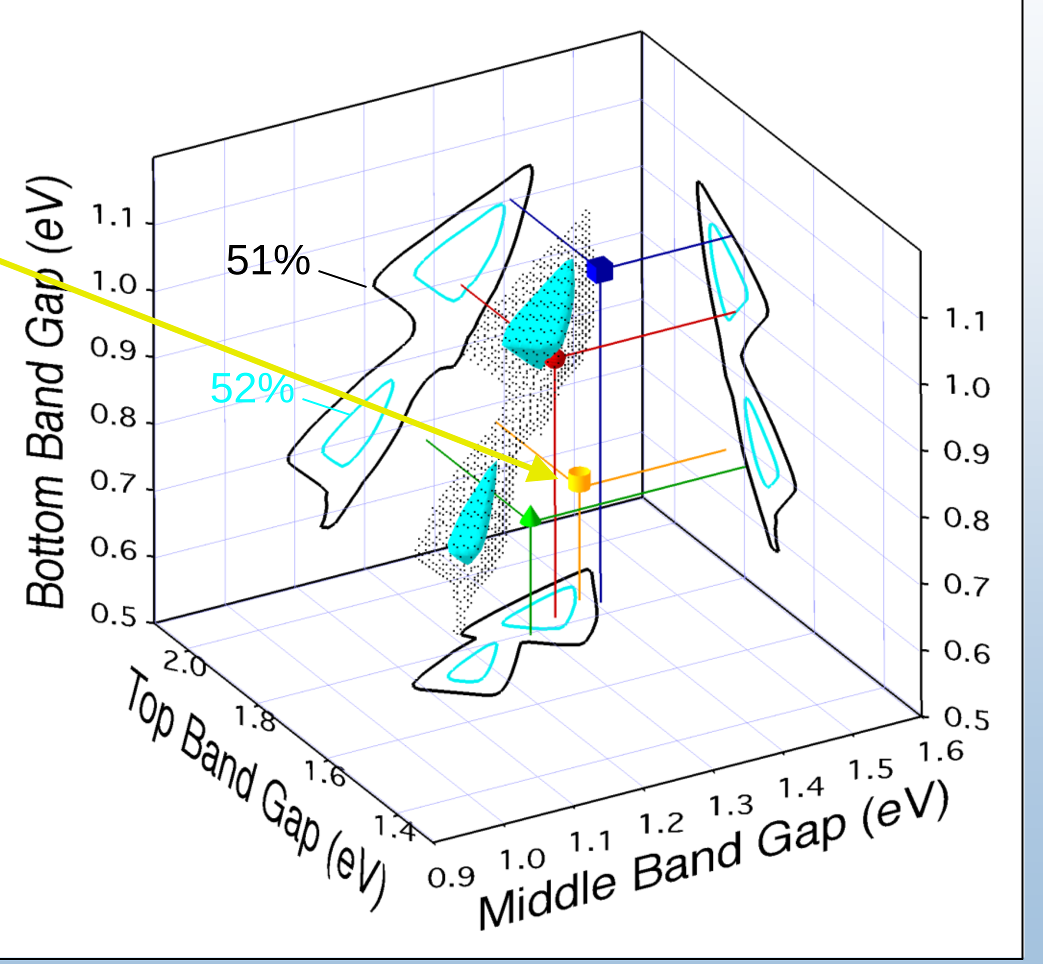


Efficiency Depends on Band Gaps

Much higher efficiencies than the commercial standard possible in principle

But bandgaps are not the sole parameter!

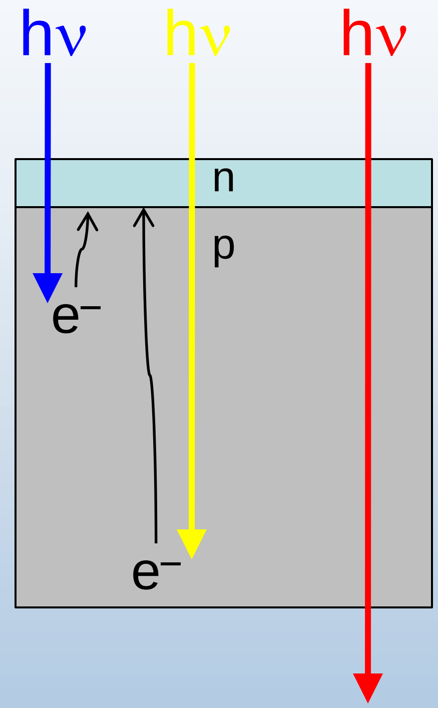
Modeled 3-junction efficiencies (500 suns)



Absorption, Collection

Want:
• strong photon absorption
• long carrier diffusion:

$L > 1/\alpha$

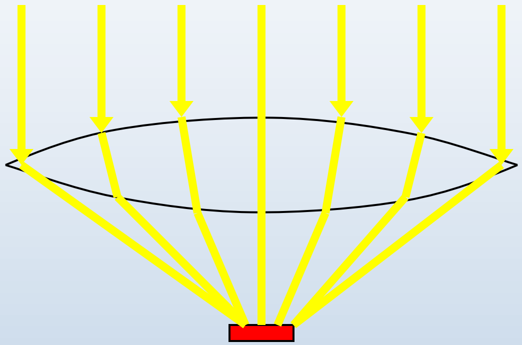


Minority-carrier diffusion length (μ, τ)

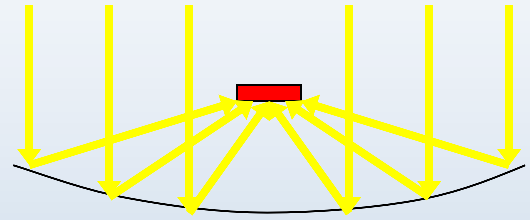
Development of CPV Technology

Optics - Lens vs Mirror

Lens



Mirror

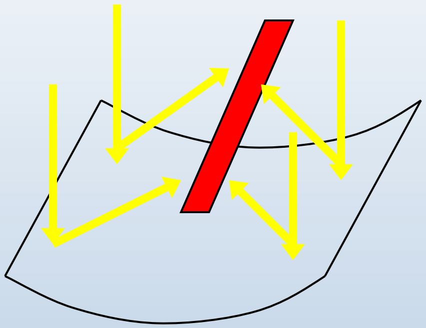


Or combination of the two

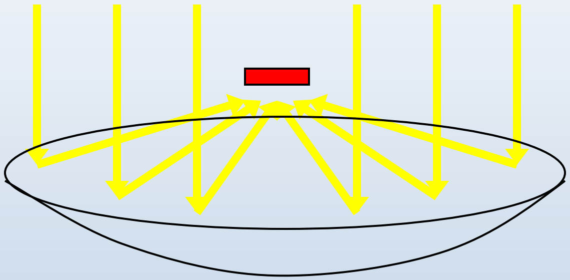
Choice has consequences for

- packaging form factor
- heat sinking
- reliability/degradation
- chromatic aberration
- cell illumination
- etc

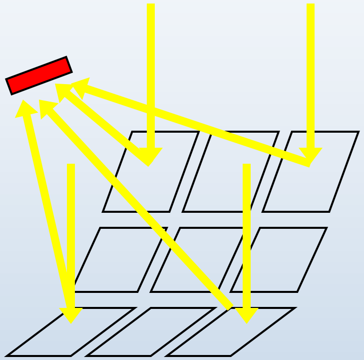
Examples of Mirror Configurations



Trough(linea
r-focus)



Dish
(Point-focus)



Heliostat

Early Demonstration of CPV Concept

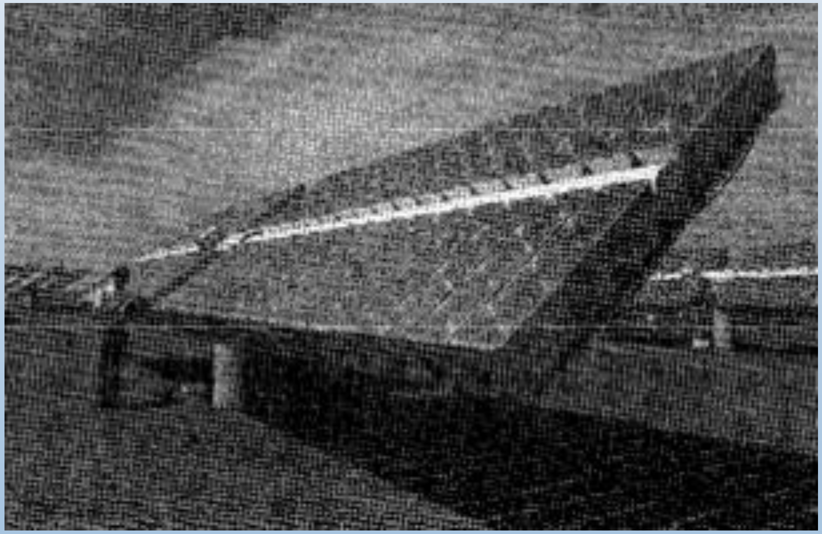
Development of CPV started not long after the 1954 invention of the modern solar cell:

Ralph (1966) demonstrated 3x concentration w. conical reflectors onto Si cells

Early CPV Systems

Sandia program developed more sophisticated systems, addressing tracking and thermal management

In this program, Martin Marrietta installed 350kW Fresnel-lens system in Saudi Arabia (1981)



Widely-Used Design Approaches

big reflective dish

Solar Systems www.nrel.gov/data/pix/Jpegs/13736.jpg

small Fresnel lenses

Probably the most widely used

www.amonix.com/sites/APS_STAR_Center_West.html

Nontraditional Design Approachs

Innovations in Mechanics

Low-profile tracking

www.soliant-energy.com

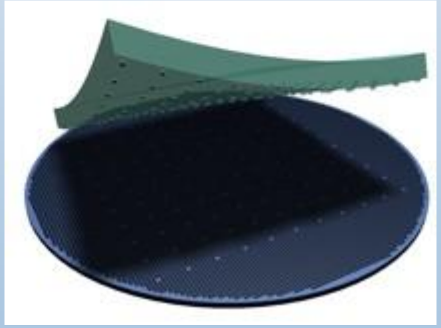
Small heliostats with coupled mirrors

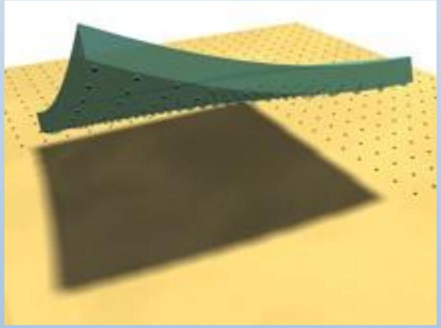
energyinnovations.com/ sunflower250.html

seedmagazine.com/news/2006/05/cleantech.php

Microsystems-enabled Concepts

Parallel printing of very small cells
Low profile module
34% module demonstrated - Semprius

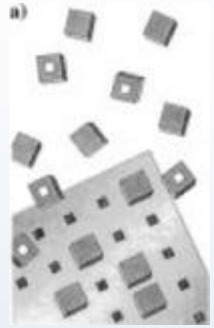




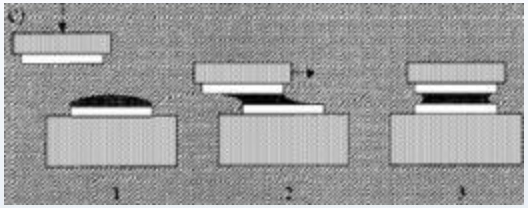
www.semprius.com

Microsystems-enabled PV

Parallel self-assembly
(Greg Nielsen, Sandia)



overview

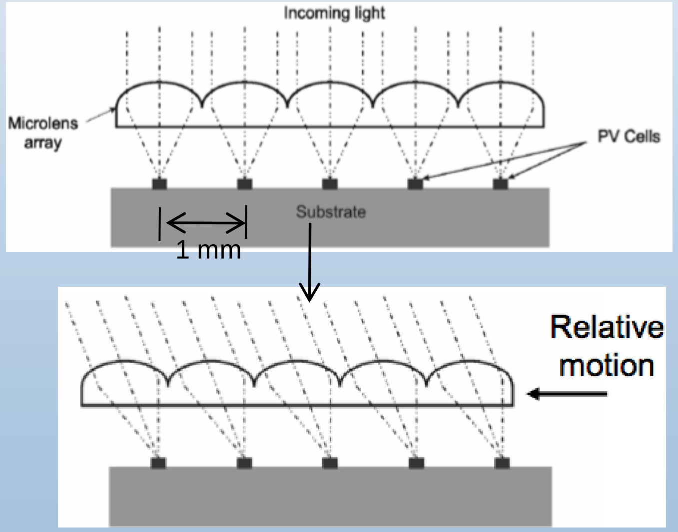


capillary self-assembly

http://www1.eere.energy.gov/solar/review_meeting/pdfs/prm2009_nielson_thin_cells.pdf

Ability to manipulate tiny cells enables new form factors

In-plane tracking
(Greg Nielsen, Sandia)



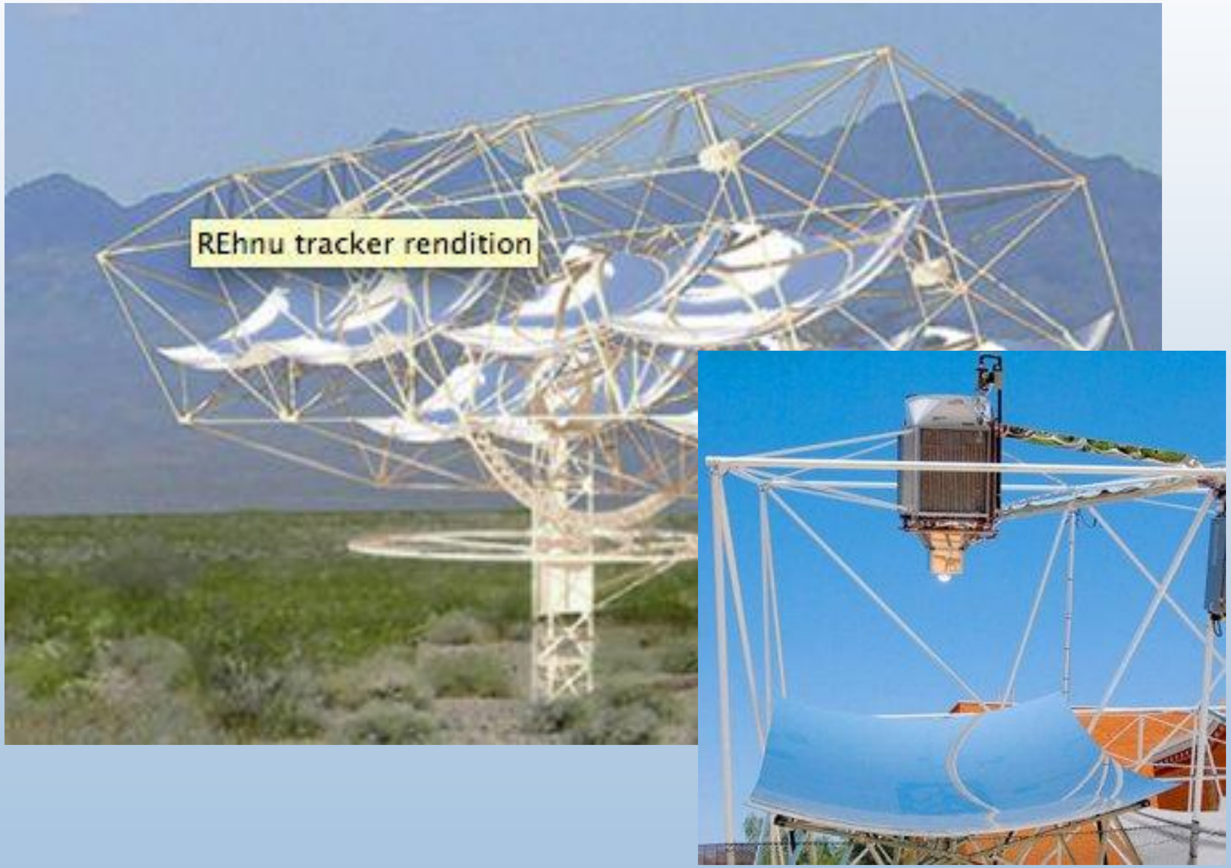
http://www1.eere.energy.gov/solar/review_meeting/pdfs/prm2009_nielson_thin_cells.pdf

Beyond the Flat-Panel-like Form

Space frame holding large dishes

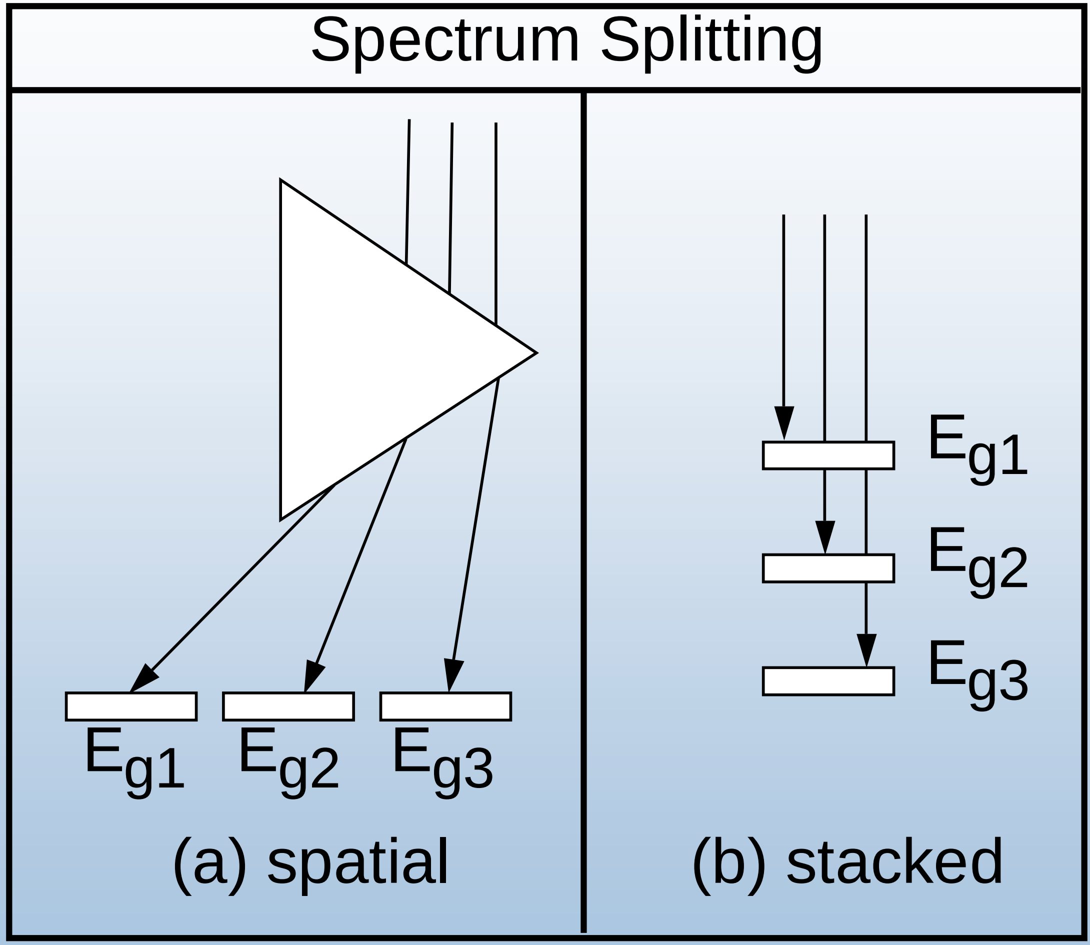
Ball optics delivers light to cells

rehnu.com



www.rehnu.com

Spectrum Splitting

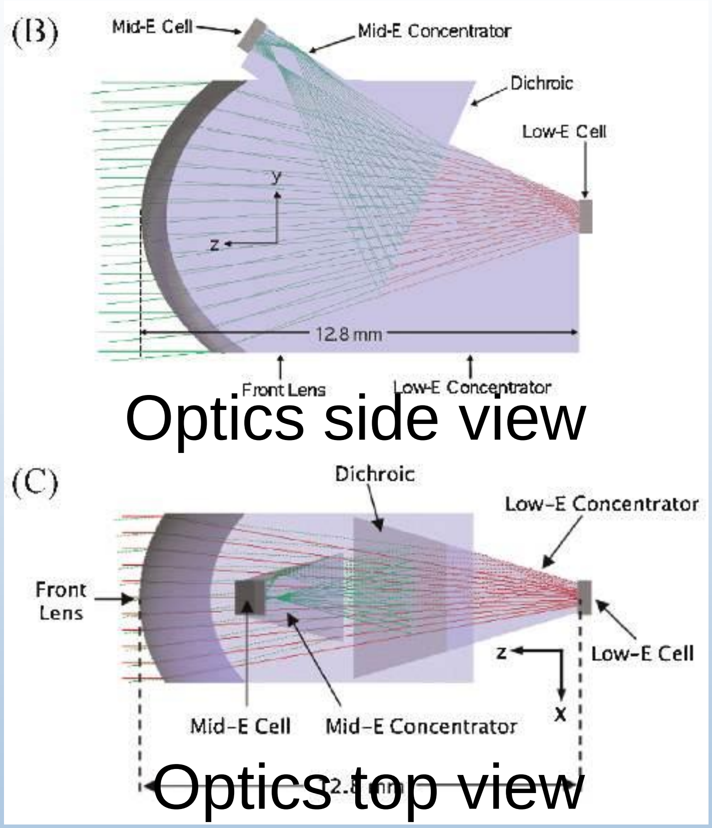


The monolithic stacked cell is an extremely elegant and practical photon sorter!

Spectrum Splitting – DARPA VHESC

Very high 38.5% module eff

20x concentration



Optics side view

Optics top view

Conclusions

CPV is a very rich field for innovation –

The many innovations to date are just a beginning